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Cryogenic infrared mission "JAXA/SPICA" with advanced cryocoolers

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Abstract

Since the next cryogenic infrared mission "JAXA/SPICA" employs advanced mechanical cryocoolers with effective radiant cooling in place of cryogen, the primary mirror, 3.5 m in diameter, and the optical bench can be maintained at 4.5 K for at least 5 years. First, the feasibility of the thermal design of the cryogenic system is presented. A 20 K-class Stirling cryocooler was then improved in cooling capacity and reliability for the mission, and the effects of contaminated working gas or new regenerator materials on cooling performance were investigated. Development of a new ^{3}He-JT (Joule–Thomson) cryocooler for use at 1.7 K is also described, along with the successful results of a cooling capacity higher than the required 10 mW. A 4 K-class cryocooler was modified and developed for higher reliability over a five-year operational life and a higher cooling capacity exceeding the current 30 mW. Finally, we discuss a system for heat rejection from cryocoolers using thermal control devices.

Keywords: Space cryogenics (F); Stirling (E); Joule–Thomson coolers (E); ^{3}He (B)

1. Introduction

In Japan, the next infrared (IR) astronomical mission of the Space Infrared Telescope for Cosmology and Astrophysics (SPICA), following ASTRO-F to be launched in 2006, has been widely discussed in terms of both scientific purposes and engineering feasibility, and a mission proposal was submitted in March 2005 to the Space Science Steering Committee of the Institute of Space and Astronautical Science (ISAS) of the Japan Aerospace Exploration Agency (JAXA). The JAXA/SPICA satellite, featuring a large primary mirror, 3.5 m in diameter, is expected to perform mid- and far-IR observations with high sensitivity and high spatial resolution as part of ongoing research into evolving galaxies and extra-solar planets, as illustrated in Fig. 1 [1]. The SPICA spacecraft is to be launched in 2013 with a H-IIA rocket, and will be transferred into a halo orbit around the Sun–Earth L2 (the second Lagrangian liberation point), as depicted in Fig. 2, where effective radiant cooling is feasible owing to solar rays and radiant heat fluxes from the Earth constantly coming from the same direction.

In the SPICA mission, a new concept for a space cryogenic system, illustrated in Fig. 3, allows unprecedented fine observations during a long period of over 5 years as shown in Fig. 4. A large primary mirror and focal plane instruments (FPI) on an optical bench are cooled to 4.5 K by state-of-the-art cryocoolers and efficient radiant cooling instead of using a massive and short-lived cryogen

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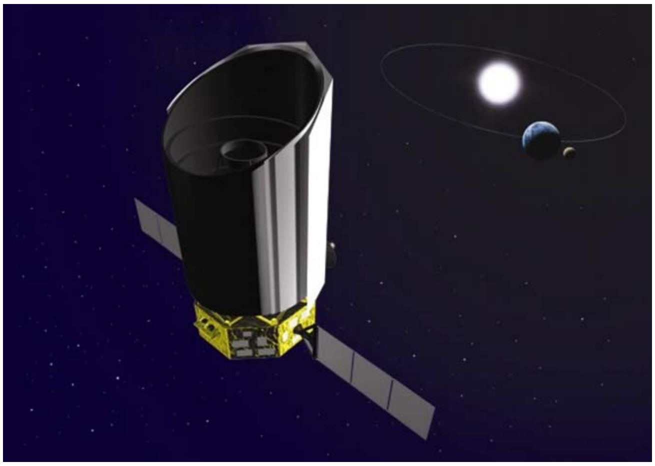

Fig. 1. Conceptual image of JAXA/SPICA.

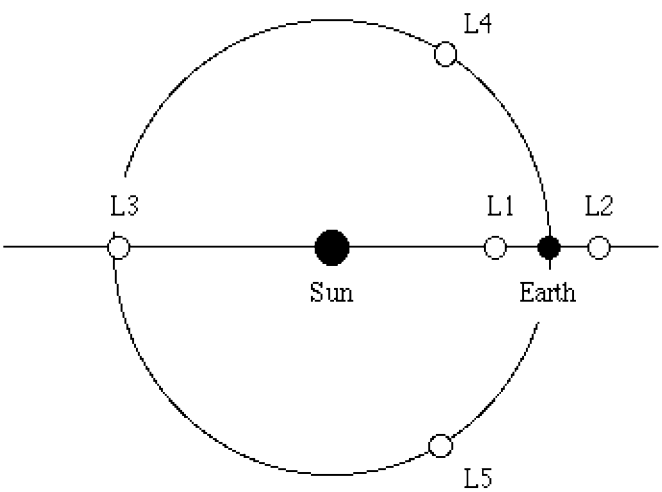

Fig. 2. Sun–Earth Lagrangian liberation points.

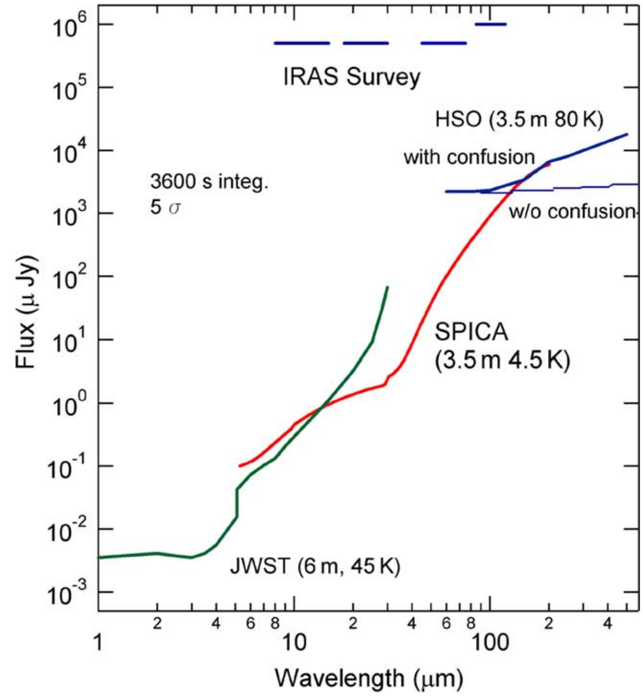

Fig. 4. Comparison with other IR missions in photometric sensitivity.

system [2]. Furthermore, a far-IR detector installed on the optical bench will be chilled to 1.7 K by a new cryocooler which is under development, based on an existing 4 K-class cryocooler developed for the mission called Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) at the Japanese Experiment Module Exposed Facility (JEM-EF) of the International Space Station (ISS) [3,4].

The thermal design of a cryogenic system for the IR telescope has already been numerically analyzed and discussed [5–7]. At the same time, a breadboard model (BBM) of the new ^{3}He-JT (Joule–Thomson) cryocooler for 1.7 K has been fabricated and examined [4], while existing cryocool-

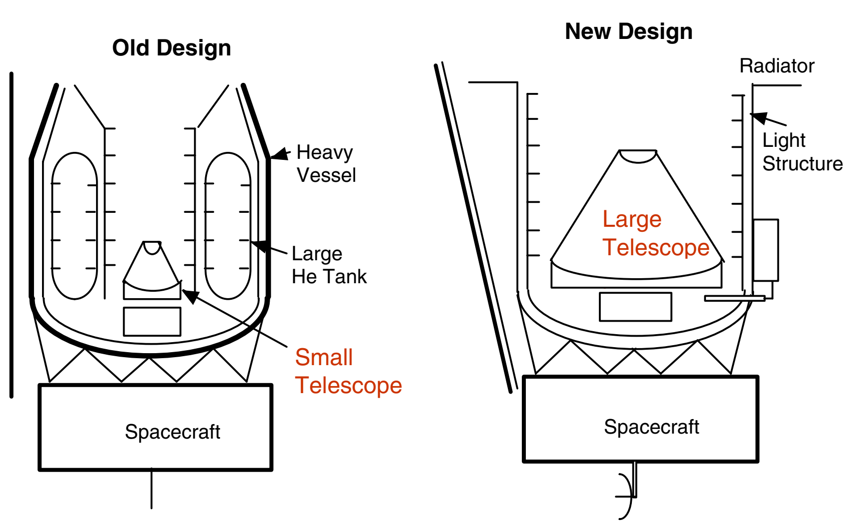

Fig. 3. Concepts of space cryogenic system.

ers such as the ^{4}He-JT cryocooler for 4.5 K and the 20 K-class Stirling cooler have been modified and upgraded in cooling capacity and reliability. In consequence, the feasibility of the SPICA mission has been confirmed in principle. This paper describes the cryogenic system to be used for the SPICA mission and the current status of development.

2. Thermal design of the cryogenic system

2.1. Configuration of the cryogenic system

The 4.5 K stage, consisting of the primary mirror and the optical bench equipped with FPI, is refrigerated by the combined methods of radiant cooling and mechanical cooling, as illustrated in Figs. 5 and 6. The primary mirror, with a diameter of 3.5 m, and the optical bench are surrounded by a baffle, a telescope shell, and outer shields, with each component thermally connected through structure supports and wire harnesses. Therefore, the heat flow between cold stages is mainly determined by the thermal conduction, since the thermal radiation between cold stages is much smaller than that between hot stages due to the small absolute values of the temperatures. In hot stages, Multi-Layer Insulation (MLI) is attached to the sun shield and to shield #3 to reduce the heat flow to colder components. The basic configuration of the cryogenic system has been analyzed and discussed in previous feasibility studies [5–7], with the thermal effects of solar array paddles on cryogenic parts considered as well.

2.2. Heat-flow analyses

Considering the cooling capacity of the existing 4 K-class cryocooler, the heat load of the 4.5 stage has to be reduced to below 30 mW. Since the Joule heating of the FPI is estimated to be 15 mW, the heat flow from the hot stages to the 4.5 K stage must remain under 15 mW. In order to determine critical design points and to optimize the telescope structure, thermal design analyses were carried out. It was assumed that structural components such as the baffle, the shields, and the telescope shell are made of an aluminum alloy. It is also noted that thermal conduction occurs through the structure supports of CFRP and the wire harnesses of Manganin. The analytical conditions are indicated in Table 1. Temperatures of the bus module, the primary mirror and the FPI are fixed in this analysis.

Calculated heat flows are depicted in Fig. 7. The results indicate that the total heat flow to the 4.5 stage is 28.42 mW, which meets the demand of less than 30 mW.

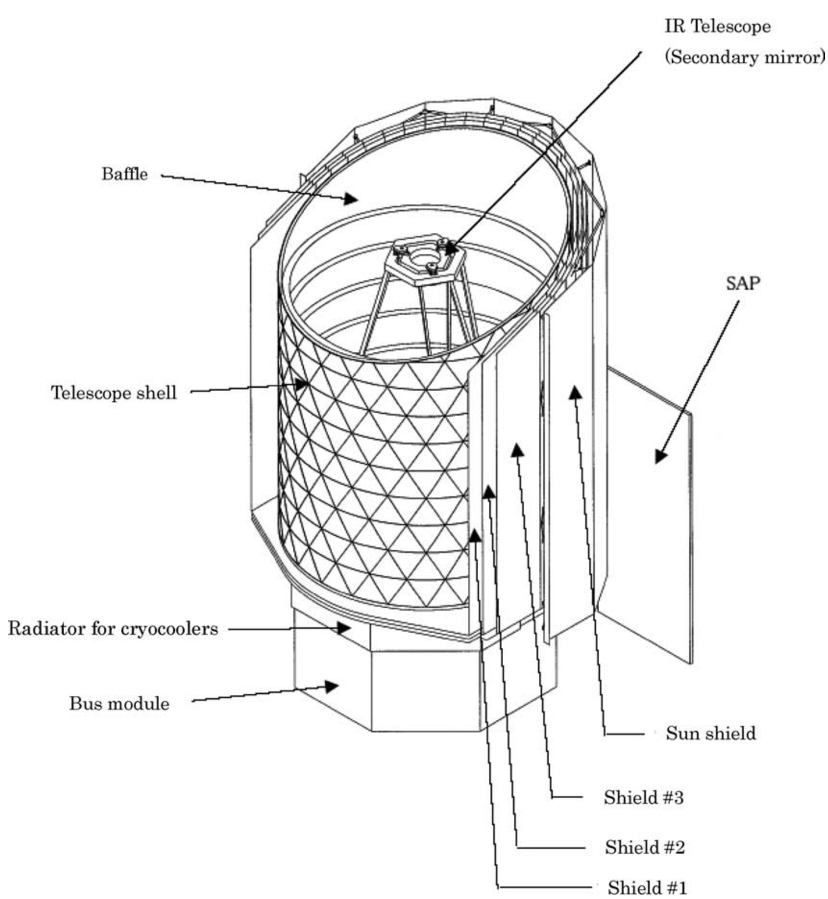

Fig. 5. SPICA spacecraft.

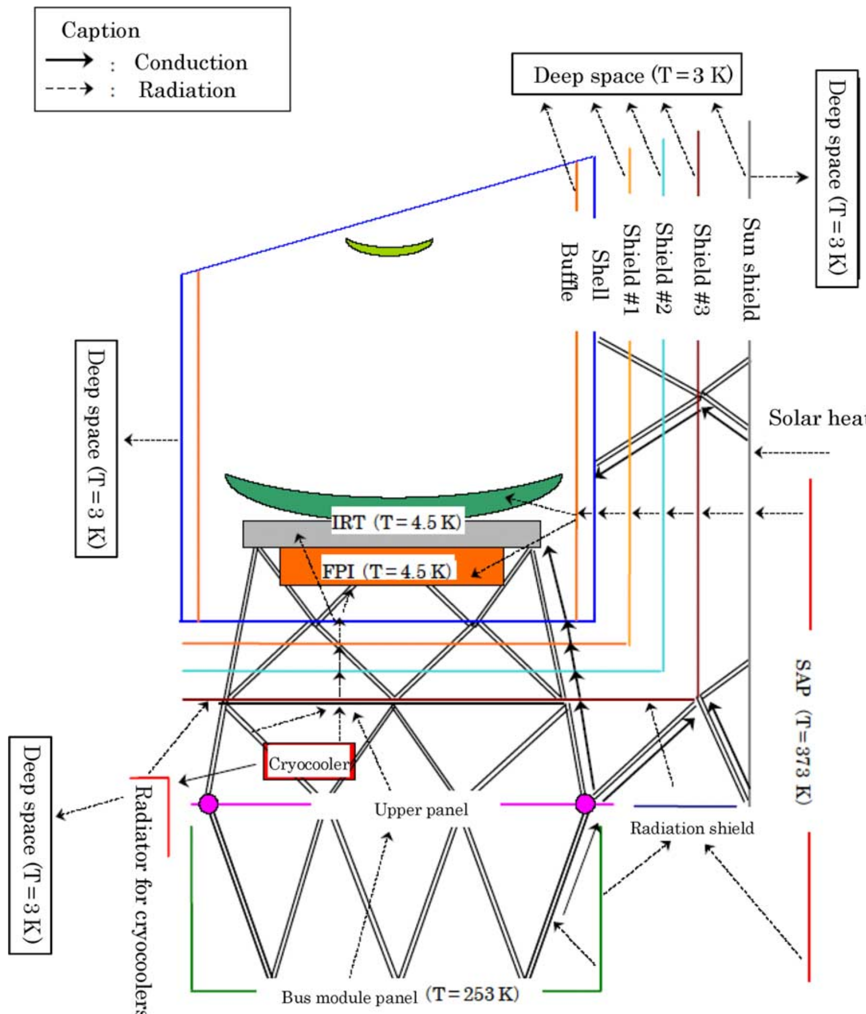

Fig. 6. Schematic drawing of the SPICA cryogenic system.

Table 1
Analytical conditions

Parameter	Value
Space background	3 K (fixed)
Bus module	253 K (fixed)
Solar array paddle (SAP)	373 K (fixed)
Primary mirror and optical bench	4.5 K (fixed)
Solar heat flux density	1376 W/m2
Exhausted heat from cryocooler compressors	550 W@294 K (W∝K)
Heat load of FPI	15 mW (fixed)
Heat rejection capacity by 4 K-class cryocooler	30 mW@4.5 K (current), >50 mW@4.5 K (upgraded)

This analytical case assumes a unified baffle with the telescope shell. In comparison to the independent baffle case, this configuration is effective in reducing the telescope mass by 160 kg and shortening the cooling time by 96 days during the initial operation phase in space, even though the temperature of the baffle increases from 9.4 K to 18.3 K.

3. Development of advanced cryocoolers

3.1. Cryocooler requirements

The IR telescope is equipped with various types of detectors called FPI on the optical bench, under the primary mirror. The SPICA mission will have enhanced sensitivity and long observation time due to the 4.5 K stage, consisting of the primary mirror and the optical bench, being cooled by cryocoolers without using consumable cryogen. In fact, these cryocoolers are indispensable to the success of the SPICA mission. The required specifications of cryocoolers for SPICA are listed in Table 2.

3.2. Improved 20 K-class cryocooler

The 20 K-class cryocooler is based on the two-stage Stirling (2ST) cryocooler developed for ASTRO-F, as shown in Fig. 8 [8]. Since the SPICA spacecraft will be equipped with four or more of the 20 K-class 2ST cryocoolers, as a part of the cryocooler for 1.7 K, 2.5 K, and

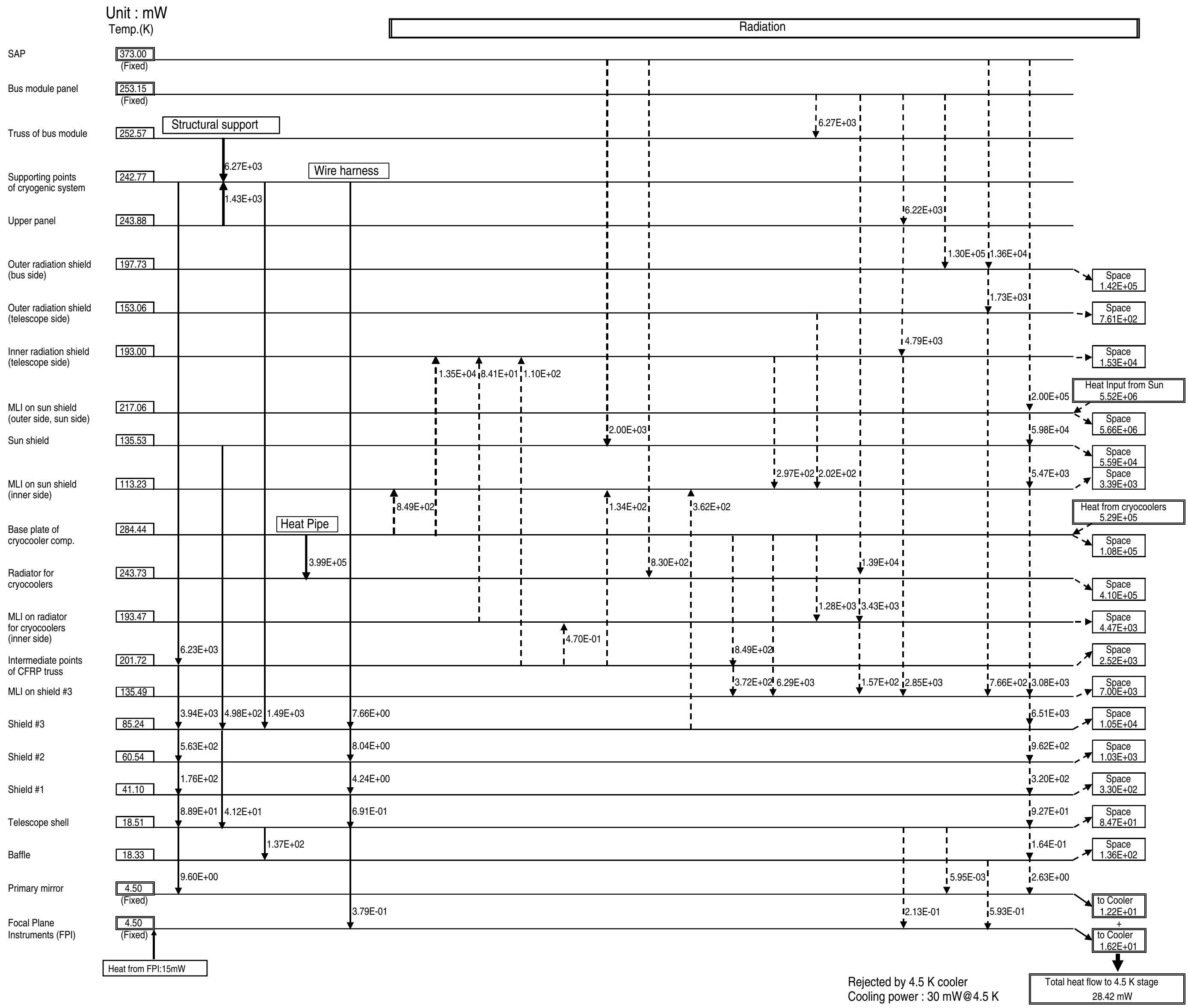

Fig. 7. Heat flows in the SPICA cryogenic system.

Table 2
Specifications of cryocoolers required for SPICA

Cooler type	Precooling for 4.5 K stage	4.5 K stage	2.5 K stage	1.7 K stage
Cooling object	N/A	Primary mirror & Si:As	Unstressed Ge:Ga	Stressed Ge:Ga
Configuration	2-stage Stirling	2ST + ^{4}He-JT	2ST + ^{3or4}He-JT	2ST + ^{3}He-JT
Cooling power	>200 mW@20 K	>30 mW@4.5 K	>10 mW@2.5 K	>10 mW@1.7 K
Driving power	< 90 W	< 160 W	< 180 W	< 180 W
Service life	>5 years	>5 years	>5 years	>5 years
R&D level	Astro-F (1 year) under improvement	JEM/SMILES (1year) under improvement	Under development	Under development

4.5 K and as a precooler during the cooling time of the IR telescope, this common 20 K-class cryocooler requires high cooling capacity and high reliability to ensure mission completion.

The increase of cooling capacity of the 20 K-class cryocooler contributes to the increase in cooling capacity of the 1–4 K JT cryocoolers connected to it. The improvement of the 4 K-class cryocooler has an especially strong effect on securing the thermal design margin of the cryogenic system.

Initially, the diameter of the second cylinder of the 2ST displacer was extended from 7 mm to 8 mm. As a result,

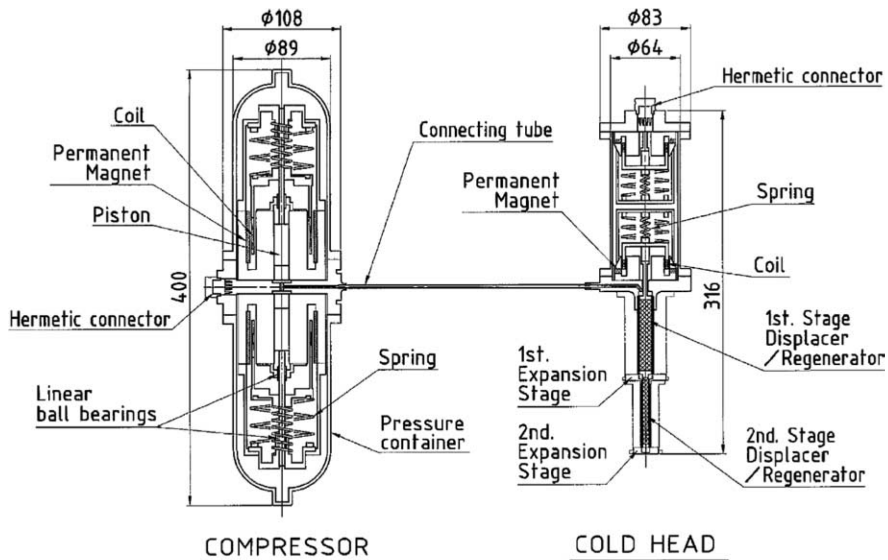

Fig. 8. 20 K-class two-stage Stirling cryocooler.

the cooling capacity was increased from 200 mW to 325 mW at 20 K in the second stage, when the first stage rejects a heat load of 1 W at 90 K with an input electric power of 90 W. In addition, other efforts to improve the second regenerator are currently attempting to reach temperatures lower than 20 K. For example, stainless steel meshes in the second regenerator were replaced with meshes coated with lead of higher volumetric specific heat, and then the cooling performance was re-evaluated.

In addition, in order to improve the reliability of the 2ST cryocooler, the effects of contaminated working ^{4}He gas on the cooling performance were investigated. CO_2 gas at 0–5000 ppm and N_2 gas at 0–3000 ppm in volume was mixed with the working gas. The results obtained are shown in Fig. 9. Fig. 9(a) for the CO_2 case indicates that the temperature of the first stage sharply increases when the CO_2 gas exceeds 500 ppm. The CO_2 gas is supposedly solidified at both the first and the second stages in the 2ST cryocooler, because the solidification temperature of the CO_2 gas is within the temperature range of the first-stage displacer. However, Fig. 9(b) of the N_2 case indicates that the temperature of both the first and second stages gradually increases as the amount of N_2 gas increases from 0 ppm to 5000 ppm. These results imply that the second stage is stably operated as long as the CO_2 gas (N_2 gas) are kept at less than 500 ppm (1000 ppm), and that the first stage is vulnerable to working gas contamination. It is also found that contamination of the working gas leads to irregular motion of the cold head.

3.3. New 1 K-class cryocooler

Since the lowest temperature of 1.7 K in the spacecraft is required for the far-IR detector, a new 1 K-class cryocooler with a cooling capacity of 10 mW at 1.7 K must be developed. In order to satisfy this cooling requirement, ^{3}He was chosen as the working gas in the JT circuit for 1.7 K because of its higher vapor pressure compared with ^{4}He. The JT circuit for ^{3}He is thermally connected with the 2ST at the 20 K stage and the 100 K stage as depicted schematically in Fig. 10 [4]. In the actual experimental configuration, the three heat exchangers of coaxial double tubes are assembled in the vacuum chamber as illustrated in Fig. 11. Since the pressure of the ^{3}He gas reaches a minimum of 8 kPa at the inlet of the JT compressors, the working gas needs to be compressed from 8 kPa at about 1.7 K to 0.7 MPa at about 300 K (room temperature) through four stages. The new JT compressors are illustrated in Fig. 12 [4]. A two-stage-unified linear vacuum pump increases the gas pressure to 0.1 MPa through the first and second compressions. A two-stage-unified linear compressor then increases the gas pressure to 0.7 MPa through the third and fourth compressions. The compressors of the 2ST cryocooler and the JT circuit are maintained at room temperature in these experiments.

The breadboard model (BBM) for the 1 K-class cryocooler has been investigated for its cooling time, its cooling capacity, the input power, and the temperature stability [4]. The recently obtained cooling capacity and the input power to the JT compressors are indicated in Fig. 13(a) and (b). These results give a higher cooling capacity of 12 mW at 1.68 K, when the input power is 162 W, which is the sum of 89.1 W for the 2ST cryocooler and 73.2 W for the JT circuit. More cooling power than the required 10 mW at 1.7 K has thus been experimentally verified on the ground test with low input power. Hereafter, the reliability for over-five-year operation must be improved and evaluated, especially the reliability of the JT compressors, the 20 μm diameter orifice valve, and the needle valve for the bypass line.

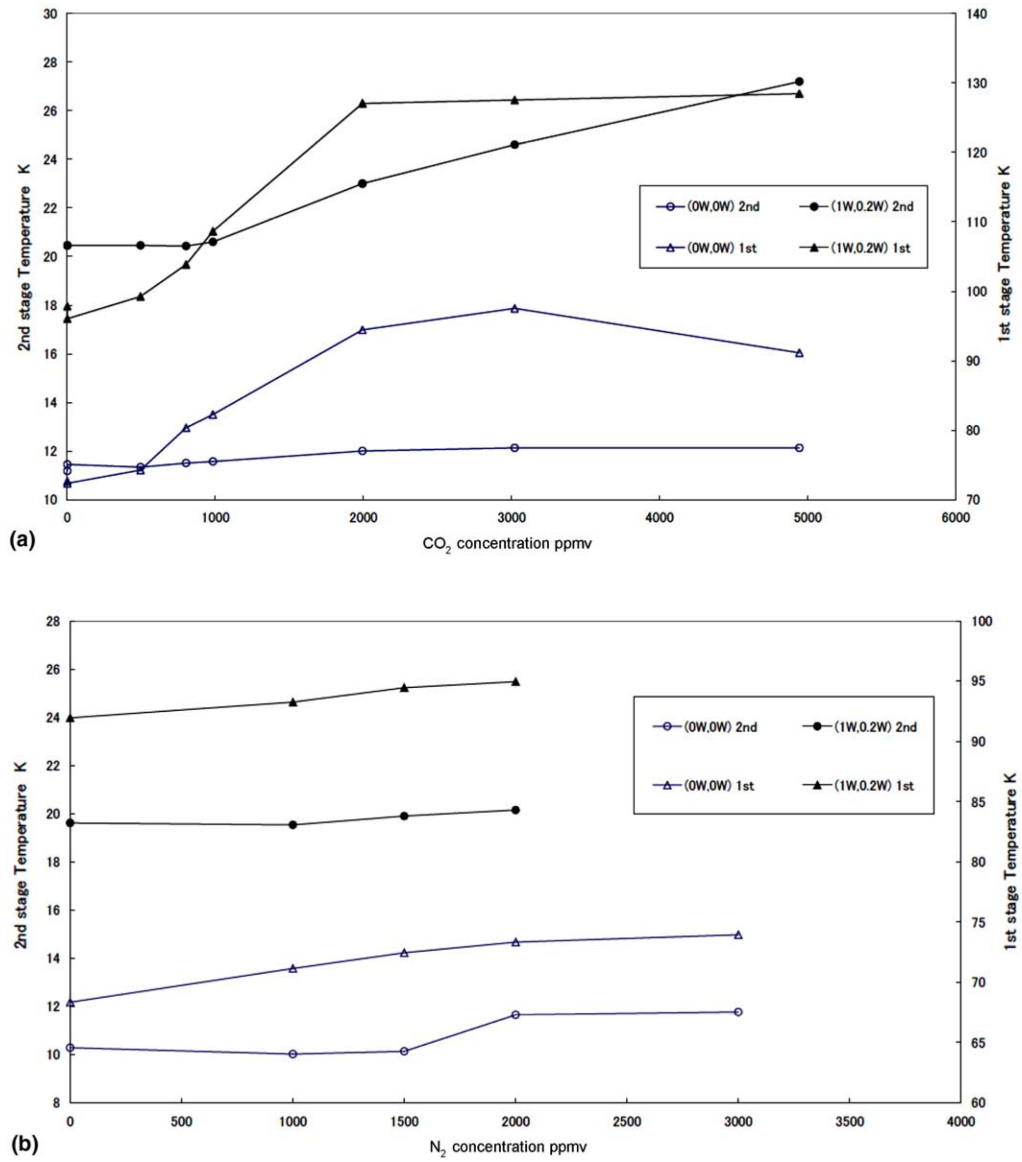

Fig. 9. Cooling performance of a two-stage Stirling cryocooler with contaminated working gas: (a) contaminated case with CO_2 gas and (b) contaminated case with N_2 gas.

3.4. Upgraded 4 K-class cryocooler

As described above, the primary mirror and the optical bench are cooled down to 4.5 K by the cryocooler with the assistance of radiant cooling, though another 4 K-class cryocooler is needed for precooling in order to quickly reach a steady state for the early startup of observations [2]. The 4 K-class cryocooler, consisting of a two-stage Stirling (2ST) cryocooler for 20 K and a Joule–Thomson (JT) circuit with ^{4}He gas for 4.5 K, had to be drastically improved in both cooling capacity and reliability over the one developed for the ISS/JEM/SMILES mission [3]. As described in the previous section, it has been experimentally confirmed that the cooling capacity at the 4.5 K stage can be increased from 30 mW to 50 mW by applying compact and efficient JT compressors developed for 1.7 K.

Since the SPICA mission requires operation of the cryocoolers for five years or longer, compared to one year for the JEM/SMILES mission, the 2ST and JT cryocoolers must have high reliability, especially regarding the reduction of vibration from the compressors and the maintenance of high-purity working gas using outgas control.

4. Heat-rejection system

Advanced cryocoolers are essential components of the SPICA mission. However, the heat rejection of about 600 W at 300 K from the cryocooler compressors presents an inevitable problem to solve. Thus, it is also important

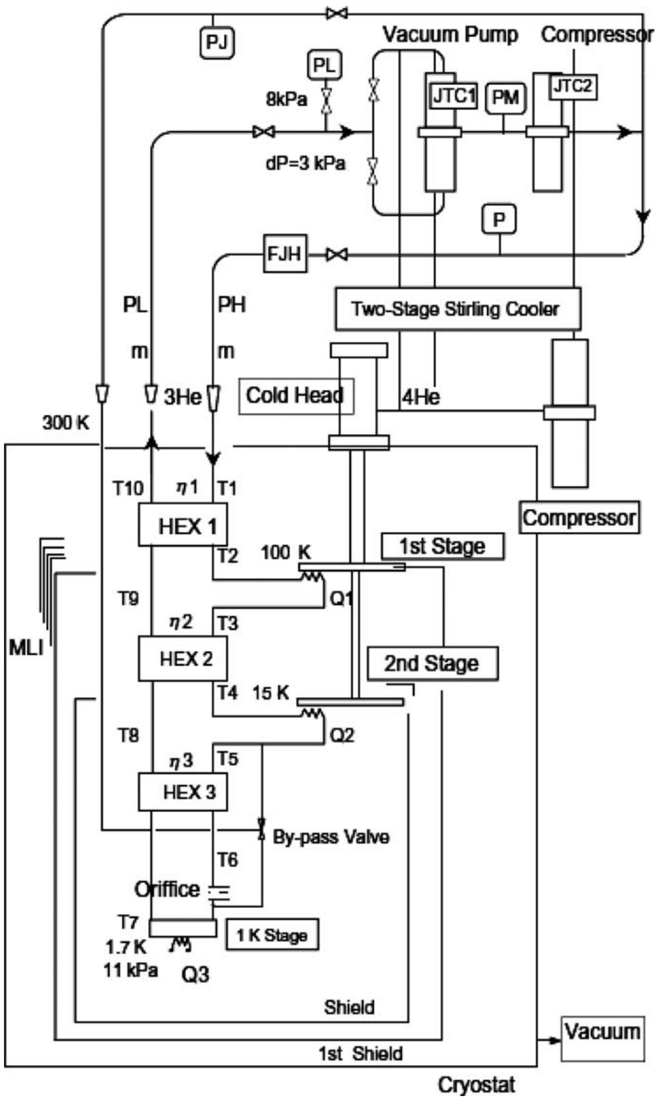

Fig. 10. Working gas flow diagram of 1 K-class cryocooler of 2ST and ^{3}He-JT.

Fig. 11. Heat exchangers and cold stages (1 K, 20 K, 100 K).

to evaluate the heat rejection system in terms of size, weight, power consumption, amount of heat transport, and reliability. The loop heat pipe (LHP), which has some advantages such as flexibility in arrangement of components and adaptability for long-distance transportation of large heat loads, has been preliminarily discussed, and a technically feasible design has been described in a previous study [7]. Obviously, a conventional heat pipe with grooved wicks has strong advantages in technology maturity and actual application in space, while being inferior in brittleness due to its rigid structure and in gravity dependence observed in the environmental ground test. The mechanical pumped loop (MPL) is also an attractive option in testability, controllability, and simplicity, though the flat-type miniature mechanical pump under development at JAXA will have to be reliable and efficient enough for long-term use in the space environment.

Further investigation into details is required to determine the configuration of the heat rejection system, while considering the parallel use of these methods to ensure reliability over the long-term mission.

5. Conclusion

The next Japanese space IR mission JAXA/SPICA will employ a cryogen-free large telescope of 4.5 K. A thermal design providing effective radiant cooling and reliable cryocooler technology are essential to the success of this ambitious astronomical mission. This paper has described the current status of design and development of the cryogenic system. It is summarized as follows.

- Thermal design analyses show that a radiant structure can reduce the heat flow to the 4.5 K stage with appropriate materials and a suitable thermal configuration.
- The 20 K-class and 4 K-class cryocoolers have been improved in cooling capacity and in reliability for over-5-year operation, based on existing coolers developed for ASTRO-F and the ISS/JEM/SMILES. Although the existing 4 K-class cryocooler satisfies the cooling requirement of 30 mW at 4.5 K, a larger capacity of 50 mW has been experimentally verified in order to secure a margin for reliable thermal design and flexible operation.
- A new 1 K-class cryocooler has been developed. The BBM successfully accomplished the required cooling capacity of 10 mW at 1.7 K with an unprecedentedly low power consumption of less than 180 W.
- A heat rejection system is necessary in order to reject exhausted heat from the cryocoolers. Valid methods such as LHP, HP and MPL must be discussed further.
- Finally, these results imply that the cryogenic system for the SPICA mission is technically feasible. However, the reliability of the cryogenic system and its components must be enhanced and validated in detail during ground tests.

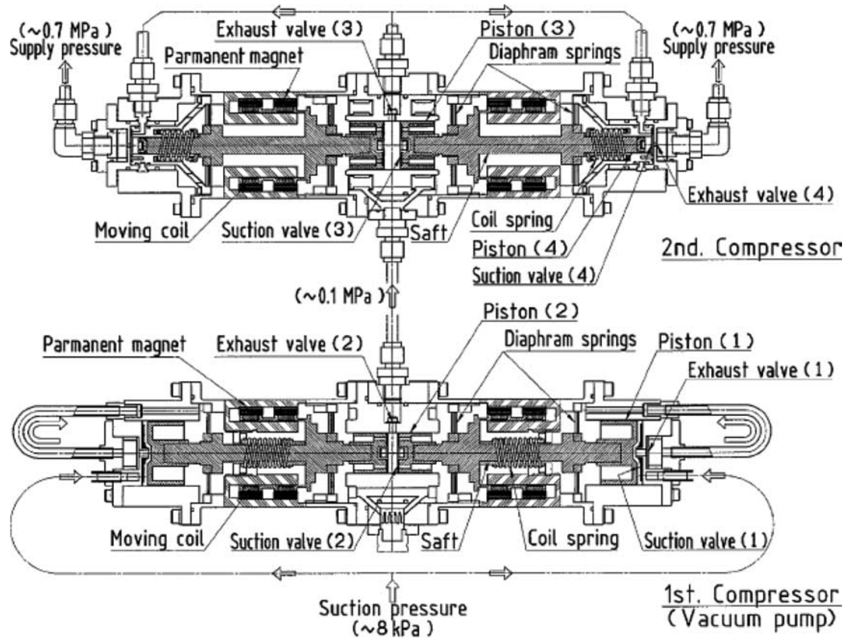

Fig. 12. 1 K-class JT compressors with four compression stages.

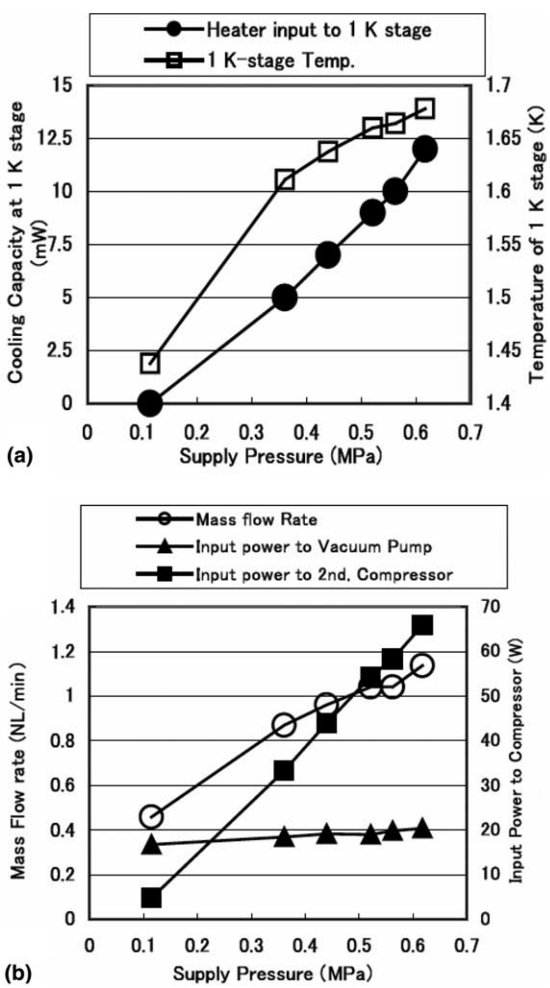

Fig. 13. Experimental results of 1 K-class ^{3}He-JT cryocooler. (a) cooling capacity and temperature at 1 K stage for JT supply pressure and (b) mass flow rate and input power to JT compressors for JT supply pressure.

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